

Expert Review

Right Ventricular Function and Echocardiographic Pressure-Volume Loops: Overview and Perioperative Clinical Implications

Usman Ahmed, MD^{*}, Feroze Mahmood, MD^{*},
Alina Nicoara, MD[†], Vahid Kiarad, MD, MPH^{*,1}

^{*}Department of Anesthesia, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA

[†]Department of Anesthesiology, Duke University Hospital, Durham, NC

Right ventricular (RV) mechanics have critical roles in cardiovascular physiology, yet their assessment remains challenging owing to the right ventricle's complex geometry and unique interaction with the pulmonary vascular system. This review explores RV structural, functional, and physiologic considerations, emphasizing their interplay with pulmonary hypertension (PH), heart failure, and perioperative outcomes. Traditional pressure- and volume-centric methods of RV evaluation, including echocardiography and right heart catheterization, often fail to provide comprehensive, load-independent measures of RV function. The integration of these measures for pressure-volume (PV) loop analysis has emerged as a valuable tool, offering insights into RV contractility, compliance, and ventriculoarterial coupling. This review highlights advances in intraoperative and noninvasive PV loop methodologies, including echocardiography-derived techniques and integration with catheter-based pressure measurements. These approaches enable detailed assessment of RV function, enhancing prognostic capabilities in such conditions as PH, heart failure with preserved ejection fraction, and postsurgical interventions like left ventricular assist device implantation and valve replacement. Despite the potential of RV PV loop analysis, its clinical adoption has been limited by technical complexities, cost, and the need for specialized expertise. This underscores the importance of standardizing PV loop acquisition techniques and validating surrogate markers, such as tricuspid annular plane systolic excursion/pulmonary artery systolic pressure ratio, to improve accessibility and utility. By providing a comprehensive overview of current and emerging methods for RV assessment, this review aims to foster a deeper understanding of RV mechanics, driving innovation in diagnostic, therapeutic, and prognostic strategies for cardiac surgeries.

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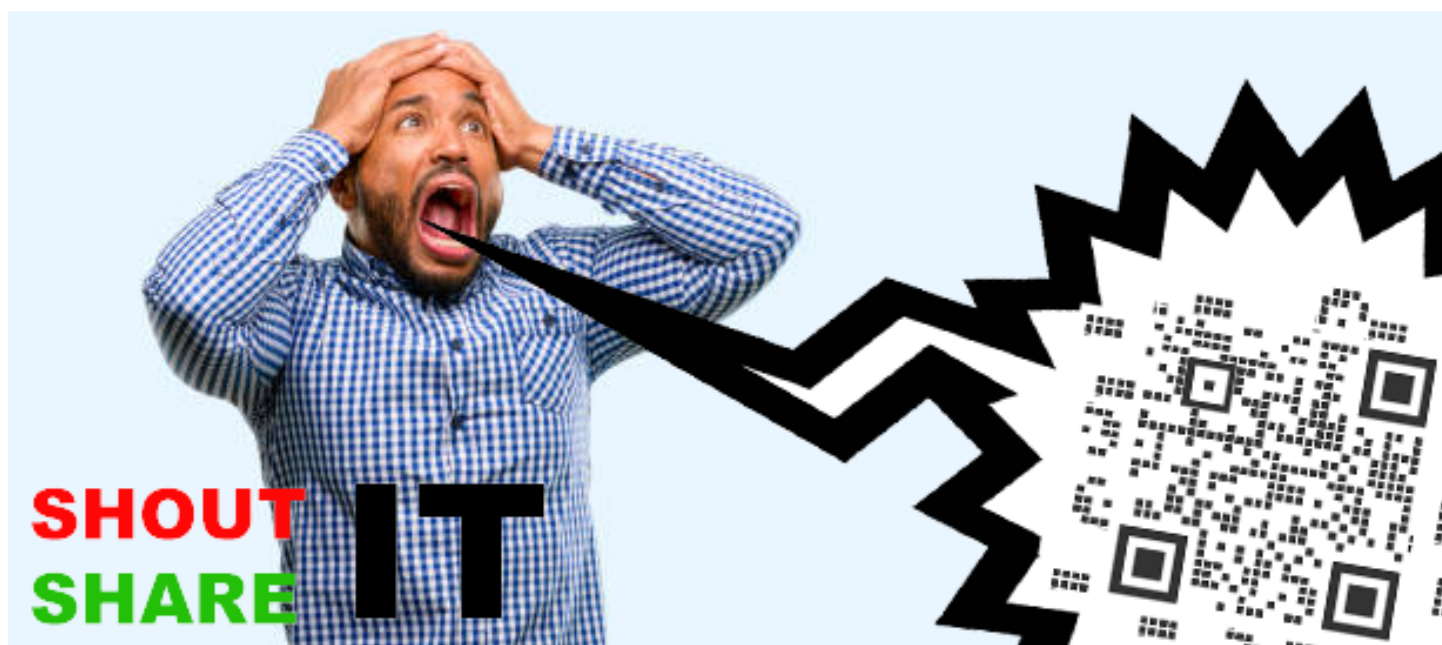
Key Words: right ventricular function; pressure-volume loop; echocardiography; ventriculoarterial coupling; heart failure; cardiac imaging

THERE HAS BEEN A resurgence of interest in identifying more sensitive and specific indices for right ventricular (RV) function assessment. Traditional perioperative RV function assessment consists of imaging or hemodynamic-derived methods, including M-mode, 2- and 3-dimensional echocardiography, and Doppler-derived parameters. While 3-dimensional (3D) echocardiography has overcome the geometric assumptions inherent in 2-dimensional (2D) RV imaging,¹⁻⁵ neither right heart catheterization nor echocardiography can reliably evaluate intrinsic RV contractility independent of

loading conditions or reflect the complex interplay between the right ventricle and the pulmonary vascular system. Considering the unique physiology, an accurate RV evaluation should include assessing the right ventricle and pulmonary vascular system as a cardiopulmonary unit using a pressure-volume (PV) relationship. RV PV loops have been studied since the late 1980s using various techniques,⁶ which have provided key insights into RV contractility and right ventricle–pulmonary artery (PA) coupling based on the end-systolic pressure-volume relationship (ESPVR). The use of RV PV loops as an intraoperative tool to assess real-time RV function during cardiac surgery has remains largely underexplored, however.⁷⁻⁹ This review article broadly examines RV structure and function and contrasts it with the left ventricle, especially regarding PV loop relationships. It also describes a proposed method for

¹Address correspondence to Vahid Kiarad, MD, MPH, Department of Anesthesia, Beth Israel Deaconess Medical Center, 330 Brookline Ave, Boston, MA 02215.

E-mail address: vk iarad@bidmc.harvard.edu (V. Kiarad).



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obtaining intraoperative RV PV loops using clinically available data and discusses their applications as markers of prognosis and therapeutic calibration.

Anatomic Considerations

The right ventricle has 3 main anatomic components: the inlet, trabeculated apical component, and outlet (infundibulum).¹⁰ This tripartite structure is essential for its function and accounts for its “peristaltic-like” contraction.¹¹ Unlike the left ventricular (LV) wall, which has 3 layers, the RV wall lacks a distinct midmyocardium. The RV wall is composed of inner longitudinal and outer circular fibers that are continuous with the superficial fibers of the left ventricle.^{12,13} Because the ventricles share common myocardial fibers, an interventricular septum, and the pericardium, dysfunction in one ventricle directly affects the other. This phenomenon, known as “ventricular interdependence,” is a major contributor to RV dysfunction in patients after cardiac surgery.¹⁴⁻¹⁹

Physiologic Considerations

Modes of RV Contraction

RV contraction involves multiple components of motion, including longitudinal, radial, and anterior-posterior shortening. In disease states, there is often a loss of shortening along one or more axes, with the sequence and extent of functional impairment varying according to the specific pathology.²⁰ In most cases of heart failure with preserved ejection fraction (HFpEF) and RV dysfunction secondary to pulmonary hypertension (PH), radial motion shows a greater decline than longitudinal shortening and appears to be a better predictor of RV function. Recent studies highlight the importance of RV radial motion as a potential screening index for PH. In contrast, heart failure with reduced ejection fraction (HFrEF) involves a significant impairment of longitudinal shortening.²¹⁻²⁴

RV Compliance and Adaptability

The right ventricle is a highly compliant chamber that adapts to fluctuations in blood flow resulting from respiration, changes in body position, and variations in LV output. Unlike systemic circulation, in which 80% of total compliance is concentrated in the aorta and great vessels, the pulmonary vasculature is a low-resistance, high-compliance system with compliance distributed across most of the arterial system, predominantly in the peripheral vessels rather than the proximal large vessels. In PH, changes in resistance and compliance are fundamentally and quantitatively distinct from those observed in systemic hypertension. Consequently, the thin-walled right ventricle is more pressure-intolerant and less capable of adapting to sudden and significant increases in afterload.^{25,26} In healthy subjects, the RV ejection phase continues well beyond the beginning of its relaxation, in contrast to the left ventricle.²⁷ This prolonged ejection phase in the right ventricle allows the pulmonary valve to remain open longer,²⁸ making

the identification of “end-systole” more challenging in the right ventricle, and contributes to the more triangular shape of the RV PV loop.²⁹ The right ventricle does not exhibit true isovolumic phases, because of its peristaltic contraction pattern and the presence of embryologically distinct inflow and outflow tracts. RV contraction begins at the inlet and proceeds toward the infundibulum.²¹ Because the left ventricle contracts as a functional syncytium, it has better-defined isovolumic contraction and relaxation periods.³⁰

Volume and Pressure-Based RV Assessment

RV function is complex, and accurately assessing RV performance requires evaluating both volume and pressure dynamics, as each provides critical but distinct information. Volume-based imaging techniques, such as echocardiography and cardiac magnetic resonance (CMR), offer structural and functional assessments, while pressure-based methods provide real-time hemodynamic insights. Understanding the strengths and limitations of each approach is essential for optimizing RV evaluation.

Volume-Based Assessment Using Echocardiography

Although advanced imaging techniques such as 3D echocardiography have addressed some limitations of 2D echocardiography, these methods primarily offer volume-focused descriptions of RV function, which are load-dependent and do not fully capture PV dynamics and the mechanics of RV PV coupling. Shimada et al³¹ reported that 3D echocardiography underestimates end-systolic volume (ESV), end-diastolic volume (EDV), and EF, which can contribute to variability in RV function assessment. Despite these limitations, 3D echocardiography remains a fast, noninvasive, and repeatable method of evaluating RV structure and function, particularly as technological advances improve image resolution, accuracy, and reproducibility.

Invasive Monitoring (Pressure-Based Assessment)

RV pressure waveform (Prv) analysis provides real-time insights into RV function during cardiac surgery by continuously measuring RV pressure through a PA catheter.³² This method is particularly useful for diagnosing such conditions RV outflow tract obstruction and assessing the capability of the right ventricle to manage increased afterload, especially in patients with PH. However, several factors limit its applicability for assessing RV function, including the effect of paced rhythms, variations with preload, and respiratory system compliance. Moreover, it lacks volume information. Pressure-based estimation of RV ejection fraction allows real-time assessment of RV function from pressure waveforms obtained during right heart catheterization, exhibiting strong correlations between pressure-based estimates and the clinical standard of cardiac magnetic resonance with reasonable sensitivity and specificity in detecting maladaptive RV responses.^{33,34} The method relies on high-fidelity pressure data and

assumptions like negligible RV volume at 0 mmHg of RV pressure (V_0), with accuracy affected by signal quality or conditions such as tricuspid regurgitation. These volume- and pressure-centric measures are listed in Table 1.

RV PV Loop Analysis

RV PV loop analysis involves tracking both pressure and volume over the entire cardiac cycle, providing a more comprehensive assessment of RV function than pressure- or volume-based methods alone (Fig 1). Animal models have been instrumental in advancing the understanding of RV PV relationships. Studies on canine hearts have demonstrated that RV contractility can be quantified using end-systolic elastance (Ees), a load-independent measure of RV contractility.³⁵ The

feasibility of PV loop analysis for assessing RV adaptation to volume overload has been demonstrated in sheep models of pulmonary regurgitation.³⁶ Studies in mice have shown how hypoxia-induced PH leads to RV dysfunction and RV-PA uncoupling using PV loops.³⁷ RV PV loop analysis provides deeper insights into RV contractility, compliance, and overall performance throughout the cardiac cycle. The RV ESPVR serves as the gold standard of RV intrinsic contractility. ESPVR is typically measured using invasive RV catheterization with a high-fidelity conductance catheter, which involves performing a series of loading manipulations while ensuring constant ventricular contractility over multiple heartbeats.³⁸ In contrast, the single-beat method calculates ESPVR from a single cardiac cycle, simplifying the process, and has been verified as a dependable substitute for the multibeat approach.

Table 1
Volume- and Pressure-Centric Measures for Evaluating RV Function

Measure	Category	Modality	Clinical Utility	Limitations
TAPSE	Volume-centric	2D echocardiography (M-mode)	Simple, reproducible measure of RV longitudinal function, prognostication in PH	Load- and angle-dependent, can be pseudonormalized in tricuspid regurgitation
RV systolic wave velocity (S')	Volume-centric	2D echocardiography	Measures RV longitudinal systolic function, correlates with prognosis	Angle-dependent, limited to basal free wall, load-dependent
FAC	Volume-centric	2D echocardiography	Assesses global RV systolic function, simple to calculate	Image quality- dependent, subjective tracing
RVLS	Volume-centric	Speckle tracking echocardiography (2D echo)	Detects subclinical dysfunction, prognostic in PH, HF	Vendor-specific variability, excludes RVOT contribution, load-dependent
Ejection fraction	Volume-centric	3D echocardiography, cardiac MRI	Global measure of RV systolic function, key prognostic marker	High cost and time for MRI, dependent on image quality for 3D echocardiography
3D RV strain imaging	Volume-centric	3D echocardiography	Advanced measure of RV mechanics, useful in remodeling and strain analysis	Requires high-quality images and specialized expertise
LGE	Volume-centric	Cardiac MRI	Identifies fibrosis and RV remodeling in advanced disease	High cost, limited availability, does not assess active function
PAP	Pressure-centric	RHC, Doppler echocardiography	Gold standard for pulmonary hypertension diagnosis, evaluates RV afterload	Doppler estimates are less accurate than direct RHC measurements
PVR	Pressure-centric	RHC	Reflects resistance in pulmonary circulation, prognostic in PH	Dependent on accurate PAP and PAWP measurement
PAC	Pressure-centric	RHC	Reflects RV afterload from pulmonary compliance, sensitive to early vascular changes	Requires precise stroke volume and pressure measurements
PAPi	Pressure-centric	RHC	Evaluates RV pulsatile function, prognostic in HF and PH	Less validated in PH, depends on accurate PASP and PADP
RVSWI	Pressure-centric	RHC	Measures RV effective work during cardiac cycle, prognostic in PH	Limited data on its use in routine practice, influenced by hemodynamics
TAPSE:PASP ratio	Both	2D echocardiography (M-mode for TAPSE), RHC (PASP)	Evaluates RV-PA coupling, incorporated into PH risk stratification	Errors in PASP estimation (via Doppler or RHC) affect accuracy
RV-PA coupling (Ees/Ea)	Both	Conductance catheter generated PV loops, RHC (pressure), echocardiography or cardiac MRI (volume)	Assesses RV adaptation to pressure overload, predicts failure	Advanced methods required, limited availability in routine practice

Abbreviations: Ea, arterial elastance; Ees, end-systolic elastance; FAC, fractional area change; HF, heart failure; LGE, late gadolinium enhancement; MRI, magnetic resonance imaging; PA, pulmonary artery; PAC, pulmonary artery compliance; PASP, pulmonary artery diastolic pressure; PAP, pulmonary artery pressure; PAPi, pulmonary artery pulsatility index; PASP, pulmonary artery systolic pressure; PH, pulmonary hypertension; PVR, pulmonary vascular resistance; RHC, right heart catheterization; RV, right ventricular; RVLS, right ventricular longitudinal strain; RVOT, right ventricular outflow tract; RVSWI, right ventricular stroke work index; TAPSE, tricuspid annular plane systolic excursion.

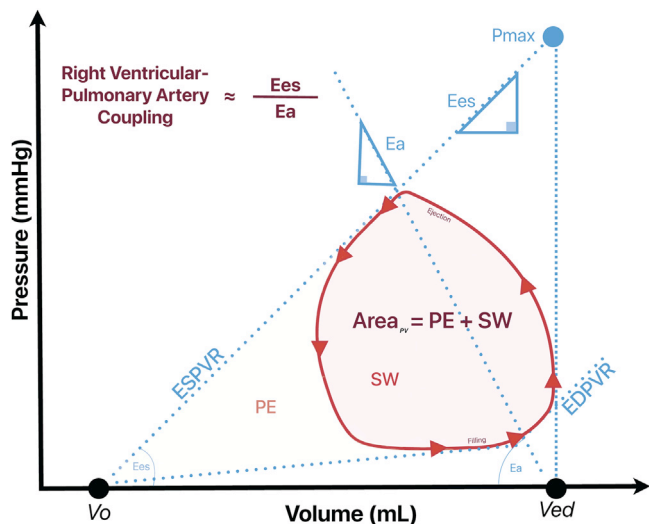


Fig 1. Representative pressure-volume loop illustrating the phases of the right ventricular (RV) cardiac cycle. Key parameters, including end-systolic pressure-volume relationship (ESPVR), end-diastolic pressure-volume relationship (EDPVR), maximal pressure (P_{max}), and volume intercept (V_0), are labeled. Additional parameters include stroke work (SW), potential energy (PE), and the relationship between arterial elastance (E_a) and end-systolic elastance (E_{es}), which depicts right ventricle–pulmonary artery coupling. The area enclosed within the loop represents the total mechanical energy of the right ventricle, with partitioning into SW and PE components.

Both methods have been extensively described in the literature for both the left ventricle and right ventricle.^{35,39,40} E_{es} is an independent measure of RV contractility representing the stiffness of the ventricle at end-systole.⁴¹ PA input impedance is the most comprehensive measure for assessing RV afterload, as it accounts for pulmonary vascular resistance, compliance, characteristic impedance, and wave reflections. However, its complex calculation and limited clinical feasibility make it impractical for routine application.⁴² Alternatively, pulmonary effective arterial elastance (E_a) serves as a composite measure that incorporates resistive, pulsatile, and passive components.⁴³ By combining mean and pulsatile loading conditions, E_a offers a physiologically relevant estimate of the total load imposed on the RV, making it a more accessible tool for clinical hemodynamic assessment.^{44–46}

Using the single-beat approach,⁴⁰ E_{es} can be determined through either the pressure method or the volumetric method. The volumetric method relies on calculating the V_0 .⁴⁷ Assuming ESPVR to be a linear relationship, the V_0 can be calculated at negative volume values. In reality, the ESPVR is always curvilinear depending on the contractile state. This nonlinear relationship can properly predict the positive value for V_0 .⁴⁸ In contrast, the pressure-based method calculates E_{es} using parameters such as P_{max} , the theoretical pressure generated within the right ventricle during a theoretical isovolumic contraction. P_{max} can be estimated by fitting a sinusoidal wave to the RV pressure waveform during the isovolumic phases of contraction and relaxation and then using the first or second derivative of the pressure waveform to identify isovolumic parts of the RV pressure waveform and determine the isovolumic intervals required for sine wave interpolation.⁴⁹ The pressure-based method may provide more accurate measurements

of E_{es} compared to the volume-based method.⁵⁰ Thorough evaluation of the right ventricle requires quantification of RV-PA coupling. This parameter (E_{es}/E_a) serves as an indicator of the efficiency of energy transfer from the RV to the PA.^{51,52} RV-PA coupling refers to the relationship between RV contractility and the afterload imposed by the PA. Adequate RV-PA coupling ensures that the right ventricle can effectively adapt to changes in afterload. This is a critical concept in managing right heart conditions, especially PH, in which small changes in afterload can significantly impact RV function.

In healthy individuals, the E_{es}/E_a ratio typically ranges from 1.0 to 2.0,⁴⁵ indicating that the RV stroke volume is efficiently transferred to the PA circulation. The E_{es}/E_a ratio exhibits a wide range, with overt RV dysfunction evident when the ratio drops to ≤ 0.8 .³⁸ In patients with PH, RV PA coupling identified occult RV dysfunction with greater sensitivity than traditional measures.⁵³ Interestingly, in contrast to the left ventricle, there is a paucity of data regarding the normal values of E_{es} and E_a for the right ventricle, suggesting that these indices may be underutilized in evaluating RV function.^{54–56} Despite their efficacy, the use of RV PV loops and ESPVR analysis are not yet widespread in clinical settings, largely due to the complexity of obtaining these measurements and the need for specialized equipment and expertise. However, advances in 3D volumetric analysis and catheter-based pressure measurements have made the intraoperative construction of RV PV loops more feasible, highlighting their potential for broader clinical application.

Alternative Methods for Constructing RV PV Loops

The mini pressure wire technique^{57,58} has been explored as an alternative means of constructing RV PV loops. The RV pressure waveform was recorded using a 0.014 Fr mini pressure wire (PressureWire, Radi; St Jude Medical), inserted through the same introducer sheath used for right heart catheterization and guided by a Swan-Ganz catheter. This micro-manometer-tipped wire allows real-time, high-fidelity (frequency response up to 25 Hz) pressure measurement directly from the right ventricle, ensuring precise waveform acquisition without the damping effects seen in fluid-filled catheter systems. Simultaneously, 3D echocardiography captured RV volume data. Pressure and volume data were aligned using customized software to match corresponding time points (key valvular events) in the cardiac cycle, which were integrated to form PV loops.^{58,59} This method has several advantages, including reduced complexity compared to conductance catheters; however, it also has limitations, including dependency on high-quality imaging, off-line postprocessing, and limited availability of the pressure wire.

Richter et al⁵⁷ presented a noninvasive technique for constructing RV PV loops using echocardiography in patients with PH. An “averaged-out” reference RV pressure waveform was generated from pooled pressure wire data and adjusted according to patient-specific isovolumic and ejection phase durations and estimated RV systolic pressure. Simultaneously, 3D echocardiography provided detailed RV volume–time

waveforms. These pressure and volume measurements were synchronized to generate accurate PV loops. The method was validated against the gold standard conductance catheter, showing strong correlations and minimal bias, indicating high accuracy. This noninvasive approach avoids the risks and complexity of invasive procedures and makes it feasible for clinical practice while allowing comprehensive assessment of RV function, RV-PA coupling, and myocardial work. However, this method requires tricuspid regurgitation for accurate pressure estimation and has not been validated in diverse populations. Moreover, these “averaged-out” reference waveforms most likely will not account for individual differences in pressure waveforms, which may compromise the accuracy of this method.

At the authors' institution, a team developed a method for obtaining intraoperative RV PV loops in cardiac surgery patients using 3D RV echocardiography and a Swan-Ganz Thermodilution VIP+ catheter (Edwards Lifesciences), which enables simultaneous RV and PA pressure measurements.⁶⁰ With this fluid-filled system with a frequency response of ~10 to 15 Hz, an adequate dynamic response was ensured through a fast flush test (“pop test”) to eliminate damping artifacts.⁶¹ Data acquisition for both volume and pressure was performed after induction of anesthesia and before surgical incision to ensure stable loading and hemodynamic conditions. RV pressure waveforms were recorded continuously using a PA catheter, and RV volume was acquired with 3D echocardiography. The waveforms were digitized using WebPlotDigitizer version 4.3 (Automeris) and synchronized by aligning 4 time points

(start and end of the cardiac cycle, end-systole, and end-diastole) to ensure accurate PV loop reconstruction. Each cycle included 15 data points, optimizing data quality while minimizing interpolation errors (Fig 2). The single-beat method was applied to derive ESPVR, Ees, Ea, and Ees/Ea (Fig 3).

By integrating invasive pressure with noninvasive echocardiographic volume assessments, this method allows intraoperative RV function monitoring, providing real-time assessment of RV contractility and coupling dynamics. The method has some notable limitations, however. It remains to be validated against the conductance catheter for accuracy, and currently it relies on postacquisition processing, which limits real-time application during surgery. The use of fluid-filled PA catheters also introduces lower fidelity, which may affect waveform precision. High-quality 3D echocardiographic imaging is essential, and artifacts or suboptimal conditions can affect results. Skilled operators are needed for precise catheter placement, and use is restricted to patients with an appropriately positioned PA catheter to capture RV waveforms. Additionally, the small sample size necessitates larger studies to confirm generalizability.

RV-PA Coupling Surrogates

Various surrogate measures are available to ascertain the degree of RV-PA coupling using a combination of invasive and noninvasive components.⁶² The tricuspid annular plane systolic excursion/PA systolic pressure (TAPSE/PASP) ratio is one of the most widely used noninvasive markers of RV

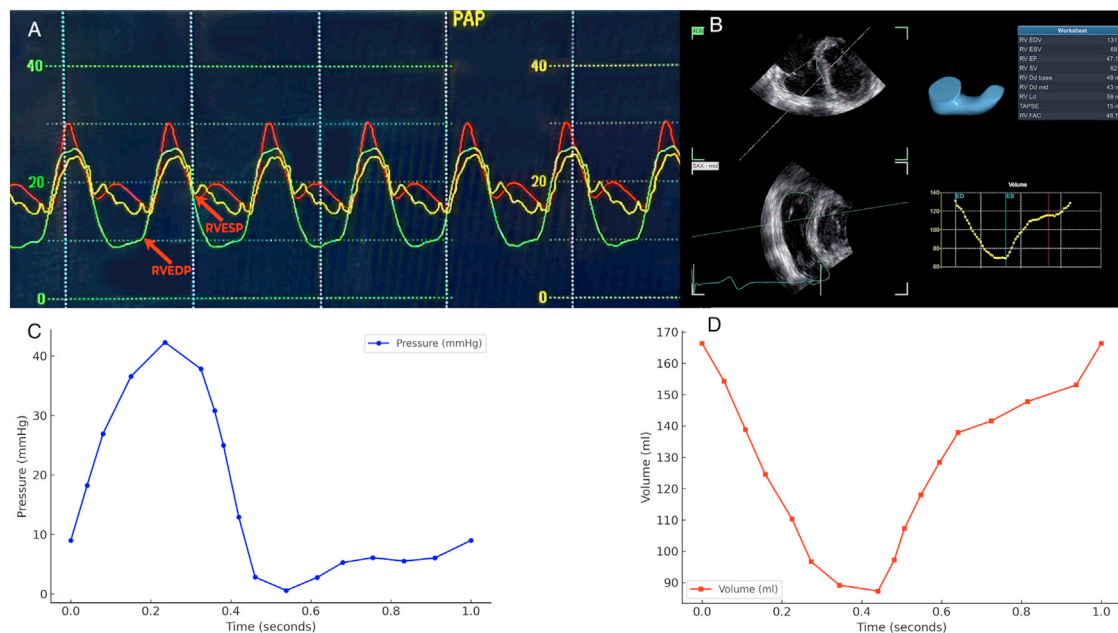


Fig 2. Intraoperative assessment of right ventricular (RV) hemodynamics using pressure and volume waveforms. (A) Continuous RV pressure waveform obtained from a pulmonary artery (PA) catheter. The red waveform represents arterial pressure, the yellow waveform represents PA pressure, and the green waveform represents RV pressure. Right ventricular end-diastolic pressure (RVEDP) and end-systolic pressure (RVESP) are indicated. (B) 3-dimensional echocardiographic assessment of RV volume. The right panel shows the reconstructed RV volume using echocardiographic data, with key volumetric parameters listed. The bottom-right panel presents the volume–time curve extracted from echocardiographic data. (C) Pressure–time waveform reconstructed from PA catheter–derived RV pressure data, showing the cyclic variations in RV pressure. (D) Volume–time waveform obtained from echocardiographic data, illustrating RV filling and emptying phases.

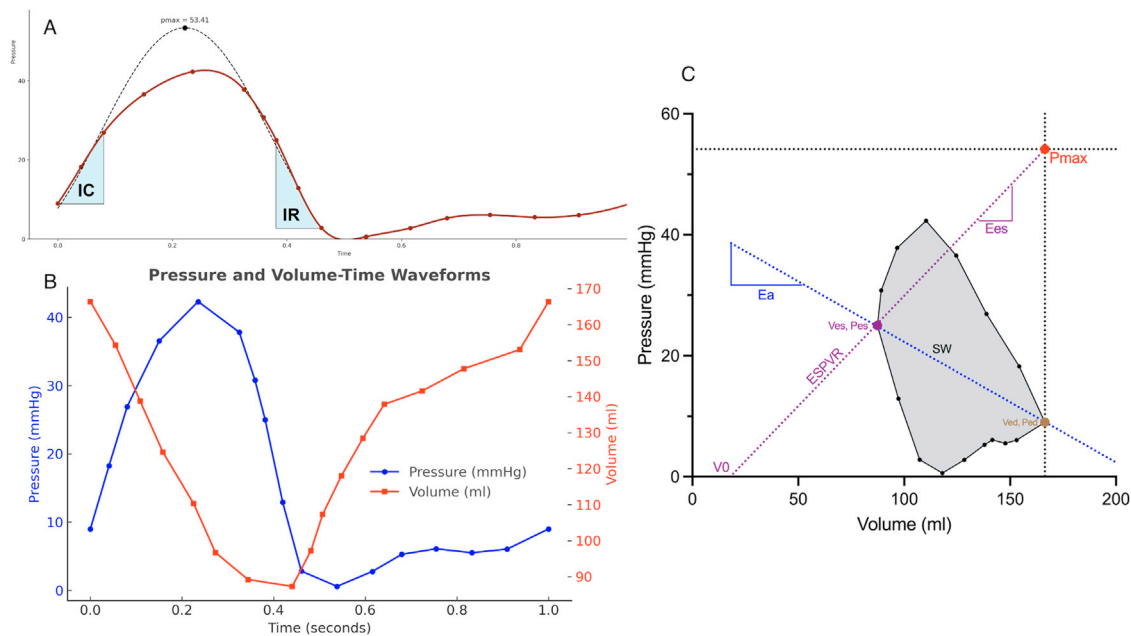


Fig 3. Reconstruction of right ventricular (RV) loops and end-systolic pressure-volume relationship (ESPVR) analysis. (A) Single-beat estimation of the RV pressure curve, fitted with a sinusoidal function to estimate Pmax. The isovolumic contraction (IC) and isovolumic relaxation (IR) phases are shaded. The peak pressure (Pmax) is marked, which is used to determine end-systolic elastance (Ees). (B) Simultaneous pressure and volume waveforms over a single cardiac cycle. The pressure waveform (blue) and volume waveform (red) illustrate the cyclic variations in RV function, with pressure peaking before volume reduction, characteristic of normal RV contraction and ejection. (C) A PV loop constructed from synchronized RV pressure and volume data. The end-systolic pressure-volume relationship (ESPVR; purple dashed line) and effective arterial elastance (Ea; blue dashed line) are plotted. The stroke work (SW) is represented by the shaded area within the PV loop. Key points, including Pmax, end-systolic pressure (Pes), and end-diastolic volume (Ved), are labeled.

coupling. It has been applied in various clinical settings for diagnosis, prognosis, and risk stratification of such conditions as PH, heart failure, and valvular heart diseases.⁶³ Despite its widespread use, the TAPSE/PASP ratio has several limitations. TAPSE is highly preload- and afterload-dependent and does not directly reflect intrinsic RV contractility, as it primarily measures longitudinal RV function.⁶⁴ As RV dysfunction progresses, TAPSE often reaches a minimum value and does not decrease further.⁶⁵ Moreover, TAPSE's plane dependency and potential for false elevation in the presence of severe tricuspid regurgitation further limit its utility.⁶⁶ Echocardiographic PASP measurements also

are influenced by the quality of the acquisition and the signal of the peak tricuspid regurgitation velocity. The TAPSE/PASP ratio also shows only a moderate correlation with the Ees/Ea.⁶⁷ Ünlü et al⁶⁸ showed that RV free-wall longitudinal strain/PASP ratio is a significant predictor of all-cause mortality and heart-lung transplantation in patients with precapillary PA hypertension; however, its use still requires validation against existing echocardiographic markers to confirm its superiority. Additionally, RV free wall strain remains load-dependent, making it susceptible to preload and afterload variations.⁶⁹ Some of these noninvasive surrogates are listed in Table 2.

Table 2
Noninvasive Surrogates for RV-PA Coupling

Measure	Description	Limitations
TAPSE/PASP	TAPSE measures the displacement of the tricuspid annulus during systole, and PASP is estimated using Doppler echocardiography.	Angle-dependent and less accurate in severe tricuspid regurgitation; reflects only longitudinal RV function.
S'/RVSP	Tissue Doppler imaging of the basal free lateral wall of the right ventricle (S') assesses systolic velocity, and RVSP reflects RV afterload.	Angle-dependent and only reflects the motion of the basal segments of the right ventricle, potentially leading to overestimation or underestimation of global RV function.
RVFAC/RVSP	RVFAC reflects the change in RV area from diastole to systole, and RVSP reflects RV afterload.	Dependent on delineation of RV endocardial borders, which can be compromised by poor image quality.
RIMP	RIMP is a Doppler-derived index combining systolic and diastolic time intervals.	Requires special Doppler recordings and understanding of physiologic principles, making it less straightforward and more time-consuming.
RVLS/PASP	RVLS is assessed by speckle-tracking echocardiography, and PASP reflects RV afterload.	Dependent on image quality and can be affected by out-of-plane motion of speckles.

Abbreviations: PASP, pulmonary artery systolic pressure; RIMP, right ventricular myocardial performance index; RV, right ventricular; RVFAC, right ventricular fractional area change; RVLS, right ventricular global longitudinal strain; RVSP, right ventricular systolic pressure; TAPSE, tricuspid annular plane systolic excursion.

Practical Implications

A key advantage of echocardiographic PV loop analysis is its potential for real-time intraoperative monitoring. During cardiac surgery, RV function may be compromised due to volume shifts, changes in pulmonary vascular resistance, and effects of mechanical ventilation. The ability to continuously track Ees and Ees/Ea intraoperatively would allow for a dynamic assessment of RV function, guiding fluid management, inotropic therapy, and mechanical circulatory support decisions in real time. This approach may improve perioperative hemodynamic optimization and help reduce the incidence of postoperative RV failure. A seminal review by Heerdt et al.⁷⁰ illustrated, through the use of porcine models, how pressure-derived parameters (such as dP/dt and peak pressure timing) can be used to assess RV function in perioperative and intensive care unit settings. The limitations of fluid-filled systems for pressure monitoring can be mitigated through optimized catheter placement, rapid flush testing, waveform filtering, and meticulous calibration to improve the reliability of PA catheter–derived RV pressure waveforms. RV-PA coupling has gained recognition as a critical marker for risk stratification in patients with PH, showing a steady decline with increasing disease severity.^{53,71,72} Because it is more sensitive than traditional RV assessment indices, it may identify the impaired RV-PA coupling earlier in the disease course to allow for more timely therapeutic interventions. Moreover, owing to its potential diagnostic and predictive value in assessing heart failure and exercise tolerance in HFpEF, RV-PA coupling may be a useful tool for monitoring disease progression and informing treatment decisions.^{53,73,74}

RV dysfunction or failure frequently occurs after LV assist device (LVAD) implantation, by a variety of mechanisms.⁷⁵ Assessing RV-PA coupling through RV ESPVR is being increasingly recognized as a method for identifying at-risk RVs and stratifying RV dysfunction in post-LVAD patients.⁷⁶ Specifically, Ees/Ea can detect occult RV dysfunction, enabling clinicians to optimize patient outcomes proactively.⁷⁷ It also can be used to optimize LVAD speed, as recent studies have indicated that increased LVAD speed improves the diastolic compliance of the RV through enhanced interventricular interaction, challenging previous assumptions based solely on systolic impairment.⁷⁸ Furthermore, pretransplantation PH remains a significant predictor of mortality following heart transplantation.⁷⁹ Since decreased RV-PA coupling reflects impaired adaptation to increased afterload, the Ees/Ea ratio derived from RV PV loops may provide useful insights for guiding therapeutic interventions aimed at improving post-transplantation outcomes. RV dysfunction is also a common complication during liver transplantation. The sensitivity of Ees/Ea for detecting subclinical changes in RV contractility is an invaluable parameter for assessing cardiovascular outcomes in liver transplant recipients.⁸⁰

RV-PA uncoupling is emerging as an independent predictor of long-term mortality after transcatheter aortic valve replacement (TAVR), irrespective of preintervention coupling status.⁸¹ Assessing the Ees/Ea response following TAVR

enhances risk stratification in these patients. Similarly, RV-PA coupling also has been identified as a strong, independent predictor of all-cause mortality in patients with tricuspid regurgitation undergoing transcatheter tricuspid valve replacement.⁸² These findings underscore the potential of Ees/Ea to inform patient selection and prognosis after valve surgery.

Both RV dysfunction and PH significantly affect outcomes in patients with HFrEF, including those undergoing cardiac resynchronization therapy (CRT).⁸³ A lack of improvement in the TAPSE/PASP ratio following CRT implantation has been shown to correlate with lower survival rates.⁸⁴ Ees/Ea holds promise as a prognostic indicator in heart failure patients undergoing CRT. This concept may extend to CRT in patients with arrhythmia-induced heart failure, an area in which the prognostic value of RV-PA coupling remains largely unexplored. Additionally, the use of RV PA coupling as a post-revascularization triage tool may provide a clinically viable method for risk stratification.⁸⁵

By providing a comprehensive, real-time assessment of RV function, echocardiographic PV loop analysis can bridge the gap between imaging-based functional assessments and invasive hemodynamic measurements. With advances in the acquisition techniques for RV PV loops, Ees/Ea now can be obtained with greater feasibility as an index of RV-PA coupling. This may enable precise calibration of management strategies based on the specific pathophysiology of RV dysfunction, allowing for its potential application in perioperative settings to aid risk stratification, decision making, and prognosis assessment. This approach may deepen the understanding of the oft-overlooked role of the right ventricle, leading to improved patient outcomes across a range of conditions. Further research is needed to validate this methodology against conductance catheter-derived PV loops before it can be widely adopted into clinical practice. Additionally, how this method compares to traditional RV function indices in predicting postoperative outcomes and whether it offers unique prognostic value in clinical decision making remain important areas for future investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships that may be considered potential competing interests. F.M. receives financial compensation for the production of educational content for GE and Abbott. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Usman Ahmed: Writing – review & editing, Writing – original draft. **Feroze Mahmood:** Writing – review & editing, Supervision, Conceptualization. **Alina Nicoara:** Writing – review & editing, Validation. **Vahid Kiarad:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Acknowledgments

The authors thank Katie Yost and Christina Short for their help with the anatomic figures.

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